A new methodology for the study of the magmatic-hydrothermal transition in felsic magmas: applications to barren and mineralised systems

by

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B.Sc Hons (University of Tasmania)

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Tasmania

Australia

May, 2004

Rio Blanco, Chile, in the background deformed Abinico Formation (Los Pelambres Formation) is overlain by the Farellones Formation. In the foreground is the tailings dam in the Rio Blanco Valley. Photograph courtesy of Dr. Peter Hollings

Statement

This thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution and, to the best of my knowledge and belief, contains no copy or paraphrase of material previously published or written by any other person, except where due reference is made in the text of the thesis.

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Acknowledgments

No man is an island, and no PhD. is ever the sole work of any one person. I gratefully acknowledge the unstinting help, and encouragement, that I have received over the years during which I have worked towards fulfilment of this project.

First and foremost I thank my family, without their love and support I could not have even begun such a project. To my parents, Thomas and Dorothea, my sisters, Sheena, Joy, Kathleen, and Susan, and my tribe of nephews and nieces, my thanks. I returned to higher education late in life, and could only contemplate doing so knowing that I had the complete and unquestioning support of everyone that is important to me. A leap in the dark is so much easier knowing that you began from a safe place, and can always return.

Particular thanks must go to my thesis supervisors, Dr. Dima Kamenetsky, and Professor Tony Crawford. Any PhD candidate knows that selection of a supervisor can be a make- or break decision, and it has been my good fortune to have chosen the best supervisors I could have hoped for. Nothing has been too much trouble, and their doors have always been open. Dima has been unstinting in introducing me the mysteries of melt inclusion techniques, and exceptionally patient with his own "sorcerers apprentice".

One fundamental problem for anyone proposing a melt inclusion study is finding melt inclusions to study. My thanks to Dr. David Cooke and the GODS team, particularly Peter Frikken and Peter Hollings, who provided the Río Blanco samples and their geological overview. Likewise, my thanks to Dr. Sharon Allen for the Okataina samples. Both sets of samples provided many insights into the processes of volatile phase exsolution, and a synthesis from both provided many more.

Particular thanks are also due to Maya Kamenetsky and Simon Stephens for their lapidary work on my behalf. Skilful lapidary work is a day-to-day requirement in melt inclusion studies, and Maya and Simon have each made important contributions to my work. Thanks also to Leonid Danyushevsky for his invaluable assistance with the LA-ICPMS analyses for this thesis. My thanks to all of the technical staff, my name is on the cover of this thesis, but you will see your work in every analysis, every thin section, and every hour I was at my desk.

More generally I must thank all of the teaching and research staff of CODES and the Earth Science department of the University of Tasmania. From my first days as an undergraduate student no doors have been closed to me, and there have always been specialists in any number of fields whose knowledge and experience has been there for the asking. I must particularly thank Professor Ross Large, as head of CODES Ross has the task of keeping the doors open and everything ticking over. Each researcher knows that we are only able to do the things that so interest us, because we have a roof over our heads, and someone else to deal with the world beyond our doors.

I must acknowledge a debt of gratitude to everyone that has made my time at University so enjoyable. Albert Einstein once said that the best job in the world for a physicist would be as a lighthouse keeper, but it would not be so for a geologist. The constant, open, and unrestricted interactions between staff, students, and external researchers are the great strength of CODES. We all gain, personally, and professionally, from the strength of our close knit community. I am not demonstrative by nature, but my candidature has been one of the best and most fulfilling periods of my life, and I have everyone at the University of Tasmania, and CODES in particular to thank.

My acknowledgments must also extend beyond the CODES community, microanalytical techniques have driven melt inclusion studies, and this thesis has been enriched by the work of several people. Electron microprobe analyses, Dr David Steele, of the Central Science Laboratory, University of Tasmania, Hobart. Laser Raman analyses, Dr Terry Mernagh, from the Minerals Division, Geoscience Australia, Canberra, and PIXE microprobe analyses Dr. Chris Ryan, and Esme van Achterbergh, CSIRO Exploration and Mining, North Ryde, Sydney, and LA-ICPMS analyses from Dr. Steve Eggins of the Australian National University, Canberra.

To one and all, my thanks.

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Abstract

This study aims to develop a robust research methodology to examine the evolution of magmatic volatile phases during the cooling of felsic magmas via detailed melt- and fluid-inclusion studies, in particular the investigation of inclusions originally containing both melt and aqueous fluid. Then, using these techniques I will examine fluid immiscibility processes in two felsic magmatic systems, one mineralised, the other barren. In particular, I address the constraints on the exsolution of magmatic vapour and aqueous liquids, and how it is manifested in quartz-hosted inclusions, as well as the nature and composition of the exsolved phases. In developing a research philosophy two factors need to be paramount, it needs to be as widely applicable as possible, and the limitations need to be recognised and explored. Thus, the results deriving from these techniques may provide a test of the methodology.

The thesis is based on two case studies, Río Blanco (Chile) and Okataina (New Zealand). The first case study involves sub-volcanic intrusives and associated extrusives from the La Copa Rhyolite, and intrusives from the Don Luis Porphyry, two post-ore rhyolitic suites from the Los Bronces-Río Blanco Porphyry Cu-Mo deposit. The second case study involves rhyolitic lavas (< 65 Ka) from the Okataina Volcanic Centre in the Taupo Volcanic Zone in New Zealand. This study is not intended to examine the geology of these systems, but rather to use them as examples of felsic systems, in diverse tectonic settings. Both as test cases for developing robust research techniques and for any information that they can provide regarding late-stage magmatic processes, particularly volatile phase exsolution, and the role of melt/fluid and liquid/vapour immiscibility.

At Río Blanco, the melt inclusion populations consist predominantly of glass inclusions and coexisting dark, inhomogeneous crystalline silicate melt inclusions (CSMI's). An important discovery from this study is the recognition that CSMI's trap volatile-rich melt, probably identical to the melt trapped as glass inclusions, and are crystallised, not "devitrified" or the product of post-magmatic alteration. Heating experiments demonstrate that both the glass and CSMI's from Río Blanco have decrepitated and degassed post-trapping, notwithstanding the apparent lack of petrographic indicators of degassing in the glass inclusions. This coexistence appears to

be a common occurrence; however, its significance seems to have been overlooked in a number of previous studies.

From an initial volatile-rich melt, aqueous volatile phases (dominantly vapour) exsolved, forming bubbly magmatic emulsions. Inherently, magmatic emulsions are metastable, and disrupt into discrete melt and vapour phases. The vapour-rich phases separated from the melt and escaped, cooling, condensing, and mixing as they did so. Río Blanco melt inclusions and fluid inclusions trapped all of these phases, in various combinations, both demonstrating the process in fine detail, and sampling the phase compositions. Analysis of the phases demonstrates partitioning of metals (Cu, Zn, and possibly Pb) into the vapour phase, its transport out of some of the magma bodies, and implies concentration by mixing and condensing to form metal-rich hypersaline fluid inclusions in the carapace of the Don Luis Porphyry.

The Okataina case study provided an invaluable counterpoint to Río Blanco. Phenocryst crystallisation pressures were supercritical, although the evidence suggests that volatile phase exsolution (VPE) occurred post- rather than pre-trapping, so that trapped magmatic emulsions are not observed. Okataina also contains coexisting CSMI's and glass inclusions, although many of the samples contains a complex array of partly crystalline silicate melt inclusions. Importantly for this study, many of the inclusions do homogenise during experimental heating, indicating that decrepitation and degassing were not as pronounced as at Río Blanco. Heating experiments showed that despite coexisting CSMI's and glass inclusions, there was only a single melt trapped. This provides evidence of the post-trapping behaviour of melt inclusions, lacking at Río Blanco. Although pre-trapping VPE did not occur to a large degree, post-trapping VPE did. Inclusions in which exsolution of an aqueous volatile phase has occurred provide a measure and sample of the amounts of fluids that were exsolved from a known quantity of melt, and may provide a method of determining the actual amounts of hydrothermal fluids that a magma body may exsolve.

In evaluating these results some inevitable limitations of the techniques have been uncovered, particularly those relating to the vagaries of melt inclusion formation and preservation, and these have been evaluated. However, qualitative, and to some extent quantitative results have been produced, some of which have been published in research journals. Together, the case studies demonstrate and sample the fine detail of the exsolution of volatile-rich phases from silicate melts, their escape from those melts, and eventual cooling and condensing to form the kinds of hypersaline hydrothermal fluids found as fluid inclusions in ore-bodies. Further, they provide insights into common post-trapping behaviours of melt inclusions, some aspects of which appear to have been misinterpreted in some published melt inclusion studies.

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Glossary

Although the first studies of magmatic inclusions are found in the work of Sorby, (1858), recent advances in microanalytical techniques have made their quantitative study possible. Consequently, meagmatic inclusion studies are a relatively new field, and as a result there is an ongoing problem of terminology. One consistent observation in magmatic inclusion studies is that typically, each suite contains numbers of inclusions, sufficiently similar to form several natural categories, although these categories vary from suite to suite. The normal solution to this problem of description is to invent a terminology of inclusion types for a particular study (type-1, type-2, type A, type B etc.). There being no requirement that the characteristics of a "type 1" inclusion in one study will correspond to a "type 1" inclusion from a different study, or a different author.

For the purpose of this thesis I have listed, and defined some of the terms I intend to use, some are conventional, and others have, of necessity, been created for this study.

- **Magmatic inclusion**; a discrete body of material, trapped inside a phenocryst at magmatic temperatures, whether fluid (melt, aqueous solution or vapour) or crystalline at the time of trapping. This term carries no genetic implications.
- **Melt inclusion**; used specifically for inclusions which I can demonstrate trapped a melt phase.
- **Glass inclusion**; a melt inclusion whose content at room temperature are primarily glass, such inclusions usually contain one or more shrinkage bubbles (fig 1) and, more rarely, contain quartz daughter crystals and/or trapped microphenocrysts.
- **CR&GT glass inclusions**; at Okataina most glass inclusions have crystal-rich (fig 2), or granular textures (fig 3). Herein, any glass inclusion other than clear glass inclusions are referred to collectively as crystal-rich and granular-textured (CR&GT) glass inclusions. This distinction is made because there may be differences in homogenisation behaviour between coexisting CR&GT and clear glass inclusions.
- **Crystallised silicate melt inclusions (CSMI's)**; all silicate inclusions (excluding microphenocryst) with completely crystalline texture (fig 4). Characteristically, they contain an interlocking mass of tiny silicate crystals ± interstitial aqueous vapour at room temperature. They have a dark, inhomogeneous appearance in transmitted light, but are white in reflected light.
- **Composite inclusions**: melt inclusion that have hetrogeneously trapped two or more phases that coexisted in the melt. Consequently, each phase can be found as primary magmatic inclusions in the same samples. Typically, they may contain

silicate melt (now glass), crystallised silicates, globules of aqueous fluid (liquid or vapour), and microphenocrysts (fig 5).

- **Microphenocryst inclusion**; a magmatic inclusion that was already crystalline at the time of trapping; these are commonly found attached to, or enclosed by glass inclusions (fig 6).
- **Fluid inclusion**; inclusions that contain significant amounts of fluid (in this study H_2O, liquid and/or vapour) at room temperature.
- **Shrinkage bubble**; sensu stricto this refers to a bubble that forms during cooling, as a result of the inclusion shrinking at a greater rate than host. This should produce a bubble that is approximately a vacuum, however, diffusion within the inclusion may introduce significant amounts of volatiles, and immiscible phase droplets may merge with the bubble.
- **Globules**; melt inclusions are described in this study whaich contain globules of 1- or 2-phase aqueous liquid ± crystalline phases. It will be demonstrated that these were co-trapped, or exsolved from the melt post-trapping. In contrast to shrinkage bubbles, which probably contain only low pressure water vapour, globules refer to higher density phases which may represent co-trapped, and therefore immiscible phases.
- **Devitrified inclusion**; used sensu stricto, where there is clear evidence that the inclusion contained a solid glass phase which has subsequently crystallised.

Contents of inclusion types used in this study

Inclusion type:	Glass	CSMI's	Composite	Fluid	Crystal-rich glass	granular-textured
CONTENTS						
Silicate glass	always	-	always	-	always	always
Shrinkage bubble(s)	always	-	always	-	always	always
Silicate daughter crystals in glass	common	-	common	-	always	common
Crystalline silicate aggregates	-	always	always	rare	-	-
Aqueous fluid	-	-	-	always	common	common
Non-silicate daughter crystals	-	common	probable	common	-	common

Glass, CSMI's, and composite inclusions are common to both Río Blanco and Okataina, crystal-rich and granular-textured glass inclusions are found only at Okataina, and fluid inclusions only at Río Blanco.

Figure 1. Clear glass inclusion; containing a small shrinkage bubble in clear rhyolitic glass.
NZL16b. 50µm scalebar

Figure 2. Crystal-rich glass inclusion; containing a large shrinkage bubble and numerous green acicular daughter crystals.
NZL4a. 50µm scalebar

Figure 3. Granular-textured glass inclusion; showing the typical brown, granular appearance. In this example the granular texture results from numerous very small 1- and 2-phase vapour-rich bubbles.
NZL1g. 50µm scalebar

Figure 4. Clear glass inclusion containing trapped zircon and apatite microphenocrysts, a large shrinkage bubble, and green daughter crystals.
NZL27b. 50µm scalebar

Figure 5. A pair of crystalline silicate melt inclusions (CSMI's); showing the characteristic inhomogeneous appearance, and associated decrepitation cracks.
Sample 9903. 50µm scalebar

Figure 6. A composite glass inclusion; containing two clear globules of single-phase aqueous liquid and a large shrinkage bubble, in clear glass. Note the shape of the globules, which suggest plastic deformation, in contrast to the shrinkage bubble, which is almost spherical.
NZL4a. 50µm scalebar

Figure 1

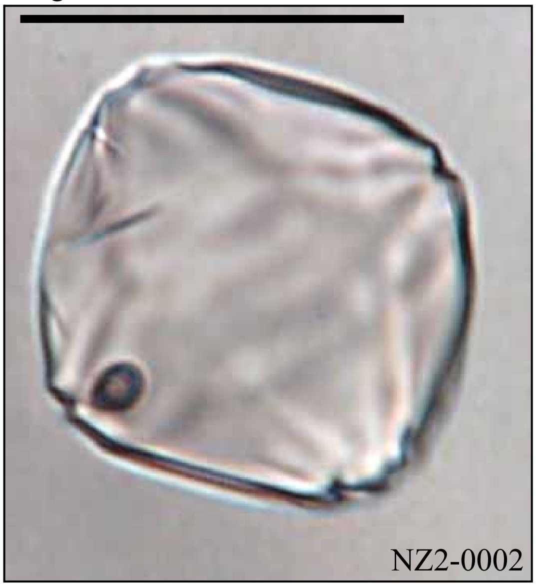

Figure 2

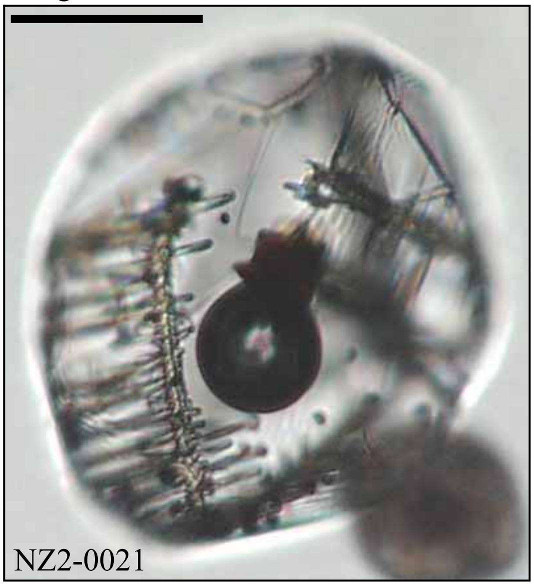

Figure 3

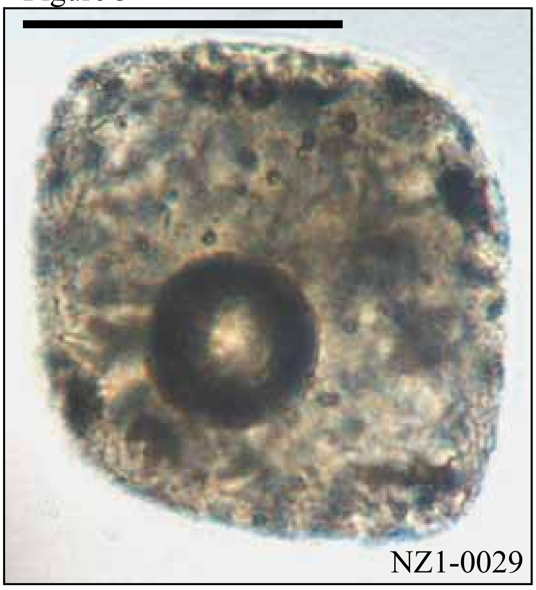

Figure 4

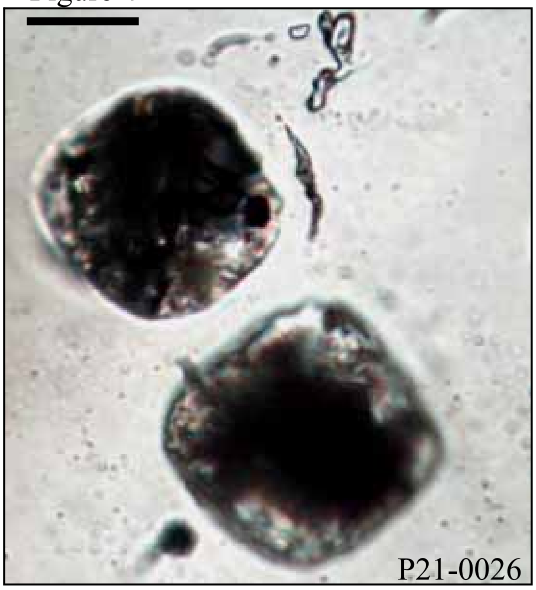

Figure 5

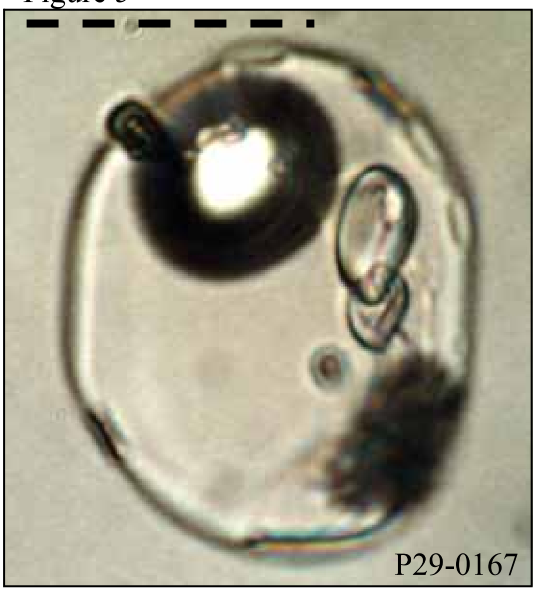

Figure 6